

Novel Features of Gamma Ray from Dark Matter

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Abstract

In this study, we present some general and novel features of gamma ray from dark matter. We find that gamma-ray spectra with sharp features exist in a wide class of dark matter models and mimic the gamma line signals. The generated gamma rays would generally have polynomial-type spectra or power-law with positive index. We illustrate our results in a model-independent framework with generic kinematic analysis. Similar results can also apply for cosmic rays or neutrino cases.

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I. INTRODUCTION

There are various compelling evidence for the existence of dark matter (DM) from sub-galactic scale to cosmological length. Searching for DM is therefore one of the primary tasks in current and future astro-particle physics experiments. Different experiments are designed for and sensitive only to some specific parameter space of enormous DM candidates [1–3]. Indirect detection of the annihilation or decaying products from DM can provide one of the most powerful complementary searches [4–6].

Satellite experiments, such as Fermi-LAT [7], can detect these energetic gamma rays from DM self-annihilates or decays. The signature would show as an excess over the featureless, continuously falling background spectrum. These searches are much more sensitive to gamma rays with localized or sharp spectrum than with wide-spreading continuous spectrum [8]. It is widely believed that detection of a sharp gamma line would be the smoking-gun for DM since, for instance, processes like $\text{DM}+\text{DM}\rightarrow 2\gamma$ can provide line signals [9].

So far, only a few cases in which sharp gamma-ray spectra other than lines have been found, such as internal bremsstrahlung [10–12] and box-shaped signals [13–15], see Ref. [8] for a recent review. However, to generate such kinds of sharp spectra, particle physics theories for DM usually have to satisfy some specific requirements. For example, to have internal bremsstrahlung the mediating particle needs to be electroweak charged, while box-shaped signals require the final on-shell particles have masses close to DM and then decay into two photons. Therefore, to test such theories, phenomenological and experimental analysis might need to be performed model by model, a not very efficient framework.

In this paper, we show in a wide class of dark matter models there exist gamma rays with sharp spectra that can mimic the line signals. The generic feature of the spectrum is that the differential gamma-ray fluxes are polynomial functions of the energy. Our discussions are based model-independent kinematics analysis, which provide a very efficient phenomenological framework for various DM theories or effective interactions. The presented method can also be used for searching neutrinos and cosmic rays from DM.

This paper is organized as follows. In Sec. II, we establish the general theoretical framework for investigating the generated spectrum from DM decay and annihilation. Later in Sec. III we illustrate how to use the formalism to calculate gamma-ray spectrum and give the general basic polynomial functions. In Sec. IV, we show how polynomial/power-law

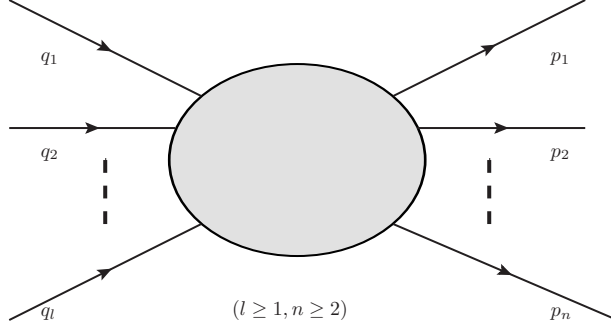


FIG. 1. Feynman diagram for general l -to- n process. $l = 1$ corresponds to the usual decay process and $l = 2$ for two-particle annihilation. q_i s and p_f s are momenta for initial and final particles. q_i s can be treated as non-relativistic $(m_i, 0, 0, 0)$.

spectrum can give rise to sharp spectra shape and mimic line signals. Finally, we summarize and conclude.

II. GENERAL THEORETICAL FRAMEWORK

Theoretically, there are enormous particle physics models for DM with huge mass range, see Refs. [2, 3] for recent reviews, and it is impractical to discuss one by one. Instead, in this paper we limit our discussion to heavy DM and assume all new or mediating particles are heavy, compared to standard model ones, which can lead us to an efficient and model-independent way for phenomenological studies.

To investigate the spectrum of generated particles, a systematic way to view the general l -to- n process can be illustrated in terms of Feynman diagram shown in Fig. 1. Although $l = 1$ and $l = 2$ correspond to the most interesting and widely studied decay and annihilation processes, respectively, here we keep an open mind for general l in cases where special types of interactions dominate. We assume all final states are standard model particles. Since from astrophysical observation, we have already known that DM particles are moving non-relativistic, we can replace initial momenta q_i with $(m_i, 0, 0, 0)$. In general m_i s do not have to be the same since some models could have multiple DM components. However, for our purpose here, only the total mass $M = m_1 + \dots + m_l$ are relevant.

The probability function σ_l or normalized distribution for a final particle over its phase

space is generally given by, for example for particle 1 with $p_1 = (E_1, \mathbf{p}_1)$,

$$\frac{d\sigma_l}{\sigma_l d^3\Omega_1} = \frac{4\pi^2}{E_1} \frac{d\sigma_l}{\sigma_l dE_1} = \frac{\int d^3\Omega_2 \dots d^3\Omega_n \delta^3\left(\sum \mathbf{p}_f + \mathbf{p}_1\right) \delta\left(\sum E_f + E_1 - \sqrt{s}\right) |\mathcal{M}|^2}{\int d^3\Omega_1 \dots d^3\Omega_n \delta^3\left(\sum \mathbf{p}_f\right) \delta\left(\sum E_f - \sqrt{s}\right) |\mathcal{M}|^2}, \quad (2.1)$$

where $s = q^2 \equiv (q_1 + q_2 + \dots + q_l)^2 \simeq M^2$, the phase space element has the following form,

$$d^3\Omega \equiv \frac{d^3\mathbf{p}}{(2\pi)^3 2E}, \quad \mathbf{p} = (p_x, p_y, p_z),$$

and $|\mathcal{M}|^2$ is the polarization-summed and squared matrix element. For signals that travel directly to detectors, like gamma ray or neutrino, we can relate to observation quantity, differential flux, through

$$\frac{d\Phi}{dE_1} = \frac{1}{4\pi} \frac{d\sigma_l}{dE_1} \int dr \left(\frac{\rho_{\text{DM}}(r)}{m} \right)^l, \quad (2.2)$$

where r is the distance from observation point to decay or annihilation point and integration is performed along line-of-sight.

The squared matrix element $|\mathcal{M}|^2$ is determined by underlying particle physics theories, or effective interaction operators. It can have various, complicated forms, as a function of Lorentz invariant $p_i \cdot p_j$,

$$|\mathcal{M}|^2 = f(p_i \cdot p_j), \quad (2.3)$$

where p_i , without confusion here, stands for both initial and final momenta, q_i and p_f . The above formula used only Lorentz invariance of \mathcal{M} . Furthermore, if all unknown or new particles that appears virtually in the bubble of Fig. 1 are heavy, much heavier than m_i , we can reduce $|\mathcal{M}|^2$ to a general polynomial function of momenta,

$$|\mathcal{M}|^2 = C_0 + C_{ij} p_i \cdot p_j + C_{ijkl} p_i \cdot p_j p_k \cdot p_l + \text{higher powers of } p_i, \quad (2.4)$$

where all the coefficients C_0, C_{ij} and C_{ijkl} are constants.

Equivalently, our above results could also be obtained from the following effective operators,

$$\delta\mathcal{L} = \sum_{i,j} \frac{\alpha_{ij}}{\Lambda^{d_{ij}-4}} \mathcal{O}_X^i \mathcal{O}_{\text{SM}}^j, \quad (2.5)$$

where $\mathcal{O}_{\text{SM}}^j$ are composite operators of standard models fields, \mathcal{O}_X^i can be a single field or composite operators of dark sector fields, d_{ij} is the mass dimension of $\mathcal{O}_X^i \mathcal{O}_{\text{SM}}^j$, and

Λ are the effective mass scale with corresponding coupling constant, α_{ij} . From the effective theory's perspective, when focusing the gamma-ray spectrum, one can impose either $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetry on $\mathcal{O}_{\text{SM}}^j$, or just the unbroken $SU(3)_C \times U(1)_Q$ symmetry instead. In the later case, only photon field, A_μ , are important.

III. FEATURES OF GAMMA-RAY SPECTRUM

The above formalism are very generic and can be used to calculate the production spectrum of any particle in the final states, such as photon, neutrino, positron/electron and proton/anti-proton. One of the particularly interested messengers is gamma ray since it can travels without deflection and points to the source. For the SM final states, without loss of generality and to get analytic compact results, we can simply assume they are all massless.

Let us start with very simple and familiar cases. From eq. 2.1, we can immediately infer that for two-body final states, the resulting distribution is always mono-energetic, namely a δ -function, $\delta(E_1 - M/2)$. This is also valid for processes with any number of initial or incoming states. Interesting particle physics models that gives such kind of gamma-line signature include, DM decay, $\text{DM} \rightarrow \nu + \gamma$, annihilation into two photons, $\text{DM} + \text{DM} \rightarrow \gamma + \gamma/Z$ and so on.

For three-body final states, it would be much more complicated due to various possible $|\mathcal{M}|^2$. Again let us first consider the simplest, although maybe unrealistic case when involving a photon, that $|\mathcal{M}|^2 = C_0$ which is constant. After performing the integral in numerator, we get the *distribution function*,

$$\frac{dP_l}{dx} \equiv \frac{d\sigma_l}{\sigma_l dE_1} = 8x, \quad 0 \leq x \equiv E_1/M \leq 1/2, \quad (3.1)$$

which is a linear function of $E_1 \equiv xM$ and $1/2$ is the kinematics endpoint. A slightly harder but realistic situation is that $|\mathcal{M}|^2 = q_i \cdot p_1$ when $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ appears in \mathcal{O}_{SM} , and we can obtain $dP_l/dx = 24x^2$ straightforwardly. Those two examples shows that the resulting gamma ray can have power-law spectrum with a positive index.

For $|\mathcal{M}|^2 \propto q_i \cdot p_j (j \neq 1)$, then we get

$$\frac{dP_l}{dx} = 12x(1-x), \quad 0 \leq x \leq 1/2. \quad (3.2)$$

all other possibilities with bilinear $p_i \cdot p_j$ can be reduced to the above three bases. For instance, $p_2 \cdot p_3 = (M^2 - 2q \cdot p_1)/2$ and $p_1 \cdot p_2 = (M^2 - 2q \cdot p_3)/2$.

We can continue to investigate cases with higher powers of momenta for more complicated effective interactions. For instance, fermionic fields or derivatives of final states would contribute more p in $|\mathcal{M}|^2$, so $\mathcal{O}_{\text{SM}} = \bar{\psi}\sigma_{\mu\nu}\psi F^{\mu\nu}$ would lead to terms like $p_i \cdot p_j p_k \cdot p_l$, see Refs. [17, 18] for other concrete examples. However, it is easy to convince oneself that the general formula would be polynomial functions of E_1 or x ,

$$\frac{dP_l}{dx} = 8D_1 x + 24D_2 x^2 + 64D_3 x^3 + \dots = \sum_{i=1} (i+1) 2^{i+1} D_i x^i, \quad 0 \leq x \leq 1/2, \quad (3.3)$$

where D_i are dimensionless constants with $\int dx \frac{dP_l}{dx} = 1$ or $\sum_i D_i = 1$, but their precise values are determined by the underlying complete theory or effective operators.

The above result, eq. 3.3, is also true for cases with more than three final states, $n > 3$. This can be proved by mathematical induction since we can always split the phase space integral in the numerator of Eq. 2.1 into $d^3\Omega_2$ and the rest, $\prod_{i=3}^n d^3\Omega_i$. Integration over the latter would be a polynomial function of E_2 and then further integration gives polynomial on E_1 .

One thing we should point out is that the polynomial form is valid in the massless approximation for final particles and under this approximation, we can get compact analytical form. In case of massive final states, we should anticipate there are also terms like $x^i(\ln x)^j$ which are sub-dominant and can be ignored when DM mass is much heavier than SM particles.

So far we have only concentrated on the “primary” photons which are produced directly from DM decay or annihilation. There are also “secondary” photons which result from the electromagnetic cascade from other final states, such as leptons, quarks, gauge bosons and Higgs particle. Such photons are usually subdominant and much softer, therefore would not affect the shape features at the high energy. Nevertheless, they can be calculated by convolution,

$$\frac{dP_l^{\text{sec}}}{dx} = \int dx' \frac{dP_l^{\text{pri}}}{dx'} \frac{dN(x')}{dx}, \quad (3.4)$$

where dP_l^{pri}/dx' in the integrand is calculated just like previous discussion, and $dN(x')/dx$ is the number distribution for primary particle with energy $x'M$ giving photons with energy xM . dN/dx can be obtained by using standard events generator, such as pythia [19].

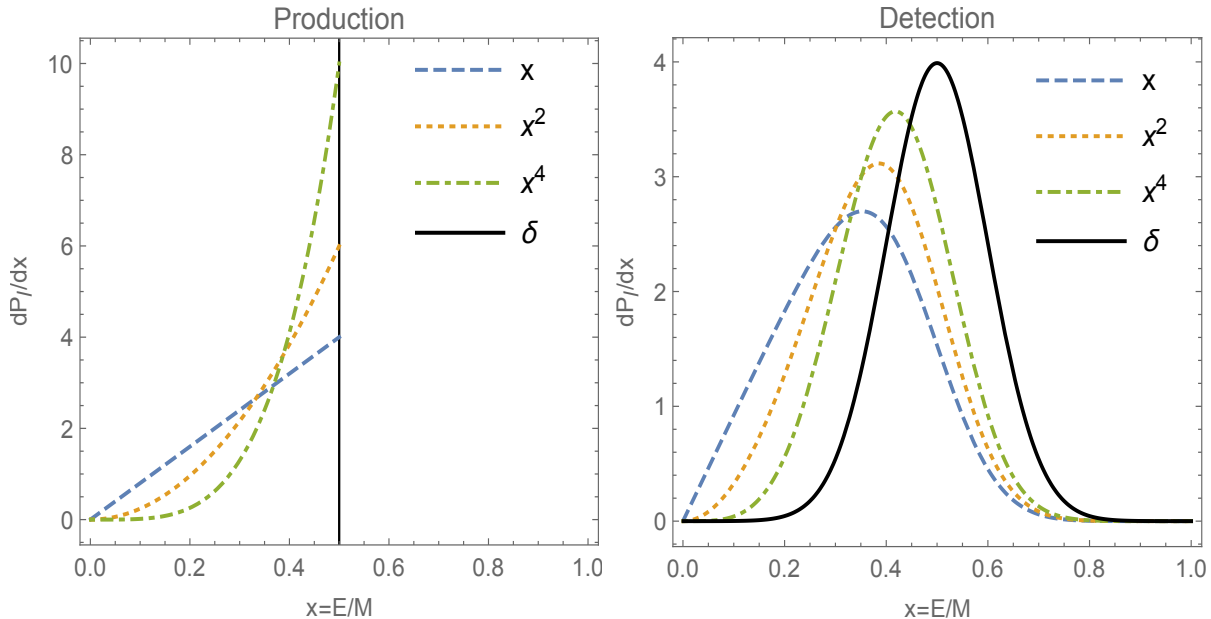


FIG. 2. Energy distributions at production (left panel) and detection (right panel) for different spectrum. The energy cut at $x = 1/2$ is due to kinematical endpoint. All spectra are normalized. See text for details.

IV. APPLICATIONS AND COMPARISONS

In this section, we show how sharp spectra for gamma ray can arise from power-law/polynomial spectrum and mimic the standard gamma-line signals. For phenomenological studies, one can either start with an UV complete theory or an effective operator and calculate the gamma-ray spectrum, or just assume some power law spectra without specifying its particle physics origin. We will take the latter approach in this section.

Due to the finite energy resolution of gamma-ray detector, the spectra measured or reconstructed can not perfectly show the original features at production point. For example, a monochromatic line ($dP_l/dx = \delta(x - 1/2)$) would display as a Gaussian distribution¹,

$$\frac{dP_l}{dx} = \int dx' \frac{\delta(x' - \frac{1}{2})}{rx' \sqrt{2\pi}} \exp \left[-\frac{(x - x')^2}{2r^2 x'^2} \right], \quad (4.1)$$

where r is the energy resolution, typical at order of 0.2. The behaviors can be seen from the black lines in Fig. 2 where the left panel gives the spectra at production and the right gives the expected ones from detection.

¹ The real situation may be more complicated. For example, Fermi-LAT collaboration convoluted with three Gaussian functions [20].

Now we simulate spectrum with power law at production and convolute with Gaussian energy dispersion. We illustrate with three simple cases,

$$\frac{dP_l}{dx} = (i + 1) 2^{i+1} x^i, \quad 0 < x < 1/2, \quad i = 1, 2, 4, \quad (4.2)$$

where the constant coefficients are due to normalization, Eq. 3.3. Their shapes are shown in Fig. 2 as dashed, dotted and dash-dotted curves, respectively. As shown, the reconstructed or expected spectra can mimic Gaussian-like signals with displaced central value and broader widths. The larger index power-law has, more similar and closer to Gaussian distribution (black curve). These findings suggest that if in future experiments a line-signal is detected, it may also be explained by or identified as power-law signals. Or equivalently, we can search for general polynomial-type signals with several parameters other than just gamma lines.

V. SUMMARY

In this paper, we have discussed some general and novel features of gamma-ray spectrum from dark matter. We have found that gamma ray can have sharp spectral shape as polynomial functions, besides gamma lines, internal bremsstrahlung and box-shaped signals. Our investigation framework is based on kinematic analysis, therefore the results are very generic, model-independent and can be used for a wide class of DM models in which new or mediating degree of freedoms are heavy, compared with standard model particles.

Based the main results, Eq. 3.3, we have shown in Fig. 2 that the polynomial or power-law spectra with an positive index can mimic the line signals for experimental searches for gamma rays or neutrinos. This suggests an efficient way for phenomenological studies that we may also start with some polynomial-type gamma-ray spectra for simulation as well as that with a particular DM model or decay/annihilation channel.

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